On the nature of the z=0 X-ray absorbers: I. Clues from an external group

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ABSTRACT

Absorption lines of O VII at redshift zero are observed in high quality *Chandra* spectra of extragalactic sightlines. The location of the absorber producing these lines, whether from the corona of the Galaxy or from the Local Group or even larger scale structure, has been a matter of debate. Here we study another poor group like our Local Group to understand the distribution of column density from galaxy to group scales. We show that we cannot yet rule out the group origin of z=0 systems. We further argue that the debate over Galactic vs. extragalactic origin of z=0 systems is premature as they likely contain both components and predict that future higher resolution observations will resolve the z=0 systems into multiple components.

Subject headings: Galaxy: halo – Local Group – galaxies: clusters: general – galaxies: clusters: individual (NGC 1600) – intergalactic medium –X-rays: galaxies: clusters

1. Introduction

Chandra and *XMM–Newton* observations have detected absorption lines due to highly ionized elements, notably O VII , at redshift zero toward all extragalactic sight lines with sufficiently high quality grating spectra. The location of the absorber producing these lines has been a matter of debate, centering primarily on two scenarios: (1) in the extended halo of our Galaxy or (2) in the Local Group (LG) or the large scale structure around the Galaxy. There are good arguments in support of both (1) and (2). Wang et al (2005) find O VII absorption

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toward the large Magellanic cloud (LMC). Bregman & Lloyd–Davies (2007) find correlated O VII line strength with soft X-ray emission from the Galaxy. Similar observations and theoretical arguments by Fang et al. (2006) support scenario (1). Galactic fountain models (Shapiro & Field 1976) also predict a hot halo around star–forming spiral galaxies, perhaps including the Galaxy itself. Models of large scale structure and galaxy formation, on the other hand, suggest that scenario (2) is a plausible source for local absorption. Comparison of O VII absorption strength with the emission measure suggests a low-density extended environment (Rasmussen et al. 2003). Direct determinations of temperature and density through photo– and collisional–ionization models of the observed absorption line ratios do not rule out either scenario (Williams et al. 2005,2006,2007), but in at least two cases the velocity dispersion and/or centroid of the O VII is inconsistent with known lower–ionization Galactic components.

The importance of this debate hinges on the total mass probed by the O VII absorption lines, which in turn depends upon the assumed path length. If the O VII absorbers are related to the Galaxy, then the associated mass is insignificant (though it can provide an important constraint on models of galaxy formation and feedback). On the other hand, if they trace the large intergalactic scale (or LG) structure, the associated baryon reservoir becomes comparable to the baryonic mass of all Local Group galaxies combined. It is well known that a fraction of LG baryons are "missing"; the total mass inferred from known galaxies and in observed cold and hot gas falls short of the dynamical mass of the LG assuming the baryon fraction is 15% of the dark matter (Kahn & Woltjer 1959; Nicastro et al. 2003 and references therein). It is likely that these missing baryons are in the not-yet observed warm-hot phase, which would be traced by O VII lines.

It is difficult to resolve this issue with simple observations, because the spectral resolution of current X-ray gratings is insufficient to resolve the absorption lines into Galactic and LG components; this is why a variety of approaches were undertaken by different groups cited above. In fact, there is almost certainly some hot gas associated with the thick disk of the Galaxy. What we need to know is whether there are components to the z=0 systems from the Galactic corona, LG, and extended structures, and if so, what is their relative contribution. In this article we attempt to answer a simple question: given what is seen in other poor groups of galaxies, can we rule out O VII absorption from intra-group gas at strengths as observed as in $z = 0$ systems? We determine, from the perspective of an observer centered within NGC 1600 (a poor group of galaxies comparable to the Local Group), how much the galactic and intragroup media would each contribute to the local warm-hot column density.

2. Method

The Local Group is a poor group of galaxies, consisting of two main galaxies and a number of satellite galaxies. Needless to say, there are other poor groups in the Universe. The physical properties of the intra-group gas, such as temperature and luminosity, and its radial distribution are governed by the group gravitational potential, not by individual galaxies. It would be of interest, therefore, to study the distribution of gas in and around individual galaxies and in the intra-group medium in a poor group similar to the Local Group.

One such group, for which *Chandra* data already exist, is NGC 1600. The high spatial resolution offered by *Chandra* is important here, as it allows exact decomposition of observed intensity profile into the galactic and group components; this will be clear in the following discussion. This group is also poor, made of three galaxies, NGC 1600, NGC 1601, and NGC 1603 of which NGC 1601 is a lenticular galaxy while the other two are ellipticals. Admittedly, the galaxies in this group are different from the LG galaxies, but the group richness is similar, so the properties of the intra-group gas, which are of interest for our purpose, should be similar, on the order-of-magnitude level, to the LG. The NGC 1600 group was observed with *Chandra* in September 2002. The details of the observations and data reduction are presented in Sivakoff, Sarazin & Carlin (2004, hereafter Paper I). While the focus of their work was on the bright elliptical galaxy NGC 1600, the entire image of the group was analyzed by these authors (see their Figure 1).

The analysis of the extended X-ray emission from the NGC 1600 group presented in Paper I is as follows. The X-ray emission extends all the way from the center of the central galaxy to the outskirts of the group. From visual inspection of the group emission, it is clear that there is a smooth transition from the central galaxy emission to the group emission. The surface brightness profile of the diffuse X-ray emission is well fit by the sum of two beta models, each defined as:

$$I_X(a) = I_0 \left[1 + \left(\frac{a}{a_c}\right)^2\right]^{-3\beta+1/2} \tag{1}$$

where one component corresponds to the interstellar medium of the central galaxy and the other to the intra-group gas; I_0 and a_c are the central surface brightness and core radius respectively. The group emission starts to dominate beyond about $25''$ from the center corresponding to 7.3 kpc at the source. The emission from the central galaxy is soft while that from the group is harder. There is also soft extended emission in/around the other two smaller galaxies. In addition there is a tail of soft emission connecting NGC 1603 and NGC 1600 (see Paper I, Figure 7). The center of the group potential lies to the northeast of the galaxy NGC 1600. The temperature of the group gas is ~ 1.5 keV as deduced from

the spectral fits, and consistent with the temperature of other X-ray bright groups. Note that 1.5 keV corresponds to a temperature of about 1.6×10^7K; the temperature range of 10^5–10^7K is called warm-hot, and it is in this temperature range most of the baryons in the low redshift Universe are believed to be hiding (Cen & Ostriker 1999; Nicastro et al. 2004).

From the temperature and the radial surface brightness profile (described as a double beta model), it is straightforward to estimate the radial density distribution. In Paper I, the X-ray emitting hot gas was fitted with an optically thin thermal plasma model (MEKAL model in XSPEC). In this model, the luminosity is simply $L = P' \times EM$ and EM, the emission measure is $\int n_e^2 dV$. The multiplicative factor P' at each wavelength depends on density, temperature and metal abundances (Mewe et al. 1985). Thus, by fitting the observed X-ray spectrum in the 0.3–8 keV band, one can determine the three free parameters of the model, viz. temperature, density and abundance. In Paper I, the metallicity of the intra-group gas was not well constrained, but was found to be consistent with approximately solar (albeit with a factor of ~ 2 uncertainty).

For the purpose of this paper, we need to determine the column density of the warm-hot gas from the perspective of an observer centered on the NGC 1600 galaxy, which can be calculated by integrating the density profile. If we were to observe distant quasars from this vantage point, our sight lines would pass through both the galaxy and group media. Our aim is to determine how much column density is contributed by each of these components.

3. Results

In Figure 1, we have plotted the observed density distribution in the NGC 1600 group. As noted above, the entire surface brightness distribution is described as a double beta model, one corresponding to the gas in the galaxy NGC 1600 and one corresponding to the group. Accordingly, we determine the density distributions of both the components; the dashed line in figure 1 is for the galaxy NGC 1600, the dot-dashed line is for the group and the solid line corresponds to the total. At the distance of the source (D=59.98 Mpc, Prugniel & Simien 1996), one arcsecond corresponds to 0.29 Kpc. As expected, the density distribution is dominated by the galactic component in the inner 20 arcseconds, beyond which the group component dominates. In the transition region around 20 arcseconds from the center, there is a bump in the density distribution which is an artifact of the fitting procedure; the exact density around this transition region, however, is immaterial for the purpose of this paper.

The column density through the gas is simply $N = \int n dr$, which we have plotted in Figure 2. Again the dashed line corresponds to the contribution by the galaxy, while the

dot-dashed line marks the group contribution and the solid line is for the total. As expected, the column density due to the galaxy asymptotically approaches a limit of $\sim 3 \times 10^{20}\mathrm{cm}^{-2}$ at around 10 kpc from the center. The group contribution is monotonically rising, and dominates the total column density beyond about 200 kpc. At a distance of 1 Mpc from the center, the group's column density is about $4.5 \times 10^{20}\mathrm{cm}^{-2}$.

In Figure 3, we have also plotted the mass distributions associated with the warm-hot gas in the galaxy and the group. As expected, the mass associated with the galaxy saturates at about $3 \times 10^8 M_\odot$. For a group size of about a Mpc ($\sim 3000''$), the mass associated with the group gas is four orders of magnitude larger, about $3.5 \times 10^{12} M_\odot$. The solid line in figure 3 corresponds to the gravitational mass of the group as calculated in Paper I; at 1Mpc this is $4 \times 10^{13} M_\odot$, implying a baryonic to dark matter ratio of about 1/10.

4. Discussion & Conclusions

As discussed in §1, we observe absorption lines of O VII at $z = 0$ in *Chandra* spectra of extragalactic objects. The column density of O VII varies from about $1.6 \times 10^{16}\mathrm{cm}^{-2}$ in Mrk 421 and Mrk 279, to $6.3 \times 10^{15}\mathrm{cm}^{-2}$ in PKS 2155-304, all within a 1σ range of $1 \times 10^{16}\mathrm{cm}^{-2}$. Assuming a fraction of oxygen in the O VII state to be unity (which is the case for the temperatures and densities observed at $z = 0$), and solar abundance to be $\log(n_O/n_H) = -3.13$, the corresponding total column density is $N_H = 2.2 \times 10^{20}\mathrm{cm}^{-2}$ for [O/H] of -1 (a tenth solar metallicity). If the metallicity is a third solar, the total column density would be $N_H = 6.7 \times 10^{19}\mathrm{cm}^{-2}$ and if the metallicity is close to solar, the corresponding $N_H = 2.2 \times 10^{19}\mathrm{cm}^{-2}$. Note that in groups and clusters of galaxies, metallicities are believed to be of the order of a third solar. However, the comparison that we make here is independent of the actual value of the metallicity assumed as long as we assume it to be the same for the local absorption systems and the group.

In the calculations leading to figures 1, 2, & 3, solar metallicity was assumed. As mentioned above, the total column density through the galaxy NGC 1600 is $N_H = 4 \times 10^{20}\mathrm{cm}^{-2}$. Thus, a column density as observed in the z=0 systems can be easily accommodated in NGC 1600, both the galaxy and the group.

There are several caveats to the above statement which we need to discuss at this stage. (1) Our Galaxy is a spiral galaxy while NGC 1600 is an elliptical, so the distribution of warm/hot gas in the two need not be similar. (2) The observed, emitting gas in the galaxy and the group NGC 1600 is too hot to contain significant amounts of O VII. (3) The density of the emitting gas is also much higher than what is observed in z=0 absorption systems

and (4) the mass of the NGC 1600 group is an order of magnitude larger than the LG; the observed high temperature is likely the result of the high mass. We discuss each of these caveats below.

Elliptical galaxies, such as NGC 1600, are known to be filled with warm hot gas, resulting in diffuse emission. On the other hand, the X-ray emission from spiral galaxies is dominated by their point source population, well correlated with the optical blue light (Palumbo et al. 1985), while extended diffuse X-ray emission is typically associated with outflows from extreme starburst activity. The column density of warm/hot gas through a normal spiral galaxy is thus likely to be much smaller than that through NGC 1600; for instance, diffuse X-ray emission has been detected in M31 but it appears to be primarily concentrated in the bulge and/or associated with hot stars in the disk (Trudolyubov et al. 2005 and references therein). We chose to analyze the NGC 1600 group because of its similarity with the Local Group (in terms of being a poor group), not because of its central galaxy. Moreover, the question at hand is not whether the $z = 0$ system can arise in the Galaxy (or NGC 1600), but rather *could the intergalactic gas in a poor group of galaxies, such as the Local Group, produce X-ray absorption at the strength observed at $z = 0$?* For this reason, the exact properties of the constituent galaxies are immaterial.

For NGC 1600, the column density derived, as shown in Figure 2, is for the gas emitting in X-rays. Because the emissivity depends strongly on emission measure, much of the *emission* comes from hotter, denser gas while the z=0 *absorption* systems would be dominated by low density diffuse gas at lower temperature ($\sim 10^6$K). Indeed, at temperatures above 10^7K, the fractional ionization of oxygen in O VII state is practically zero, so the gas observed in emission would contribute nil to O VII absorption (see, e.g., figure 4 in Mathur, Weinberg & Chen 2003 for the fractional ionization of oxygen as a function of temperature). Examination of Figure 1 in Paper I shows that the detectable diffuse emission from the NGC 1600 group extends out to about 70 kpc from the center. At about 300 kpc (1000″), the density falls to the value observed in the Mrk 421 z=0 system ($1.2 \times 10^{-4} cm^{-3}$; figure 1). At such distances, the gas could also be cooler, if it hasn't yet fallen into the group potential. Thus, instead of considering the total column density through the group, it might be more appropriate to determine the column density accumulated beyond 300 kpc. From figure 2, this turns out to be $\sim 1 \times 10^{20} cm^{-2}$, which can still accommodate the z=0 systems. The assertion of gas being cooler in the outskirts of groups/clusters appears to be justified: the intracluster gas temperature of the Coma cluster is 8.21 keV (Hughes et al. 1993). At such high temperatures, most of the gas is fully ionized, and yet emission lines of O VII, O VIII, and Ne IX were detected at the position of the cluster (Takei et al. 2007), presumably from the cooler outskirts.

It is also interesting to note here that the gas temperature in the galaxy NGC 1600, even though somewhat lower than that in the group core, is still quite hot: 0.85 keV (9.86×10^6K). The fractional ionization of oxygen in O VII state at such temperatures is still practically zero. Thus, the gas seen in emission in the galaxy NGC 1600 will *not* produce absorption lines as seen in the z=0 systems.

The total gravitational mass of the Local Group is $\sim 2 \times 10^{12} M_{\odot}$(Kahn & Woltjer 1959; Peebles 1995) which is about an order of magnitude smaller than that of the NGC 1600 group (figure 3). This leads to a column density which is also an order of magnitude smaller (if the change in mass is a result of the change in central density), or $N_H = 4 \times 10^{19}$cm, again consistent with what is observed in the z=0 systems. More importantly, smaller mass of LG would imply lower temperature than the NGC 1600 group, bringing it closer to the WHIM temperature range where fractional ionization of O VII peaks. Fang et al (2007) detected O VIII absorption line near a small group containing four galaxies, indicating that the temperature becomes higher for groups more massive than ours.

Note also that the beta models were fitted to the NGC 1600 group up to a radius of $180''$ and their extrapolation out to $1000''$ may not be appropriate. While an abrupt change in the density profile is not to be expected, and would not be physical, we need to keep this caveat in mind. Nonetheless, the analysis of the density profile of a real poor group like NGC 1600 allows us to make reasonable estimates of mass and column density profiles, as shown in figures 2 & 3. One major argument against the large-scale origin of z=0 systems was made by Collins, Shull & Giroux (2005) based on, what was claimed to be, the unacceptably excessive mass of such a structure. They showed that if the O VII absorbers are distributed in a spherical shell centered around the LG at a mean radius of $\approx$ 1Mpc, then the associated total mass would be 12 times larger than the gravitational mass of the LG (assuming a metallicity of a tenth solar and baryon to dark matter fraction of 1/6). Such excessive mass results from the assumption of the shell geometry, and to a lesser extent from the assumption of metallicity. Williams et al. (2005) have already shown that the mass can be reasonable for metallicities of a third solar and if the gas is uniformly distributed over the sphere of $\approx$ 1Mpc radius. With even a more realistic density profile, as shown here by a beta model for NGC 1600, the baryonic mass lies well below 1/6 of the dark matter mass as is clear from figure 3 (and the numbers given in §3).

Clearly, there are several poor groups in the nearby Universe, and NGC 1600 is just one of them. We will exploit the *Chandra* archive and perform similar analysis of other poor groups to characterize their similarities and differences to draw further inferences on the nature of the z=0 systems. In particular, it would be of interest to find a group as massive as the LG and containing spiral galaxies.

Of course, in studying an external group of galaxies we cannot make *direct* inferences about the Local Group's matter content, and we are thus not claiming a definitive Local Group origin for the $z = 0$ X-ray absorption systems. However, it appears reasonable to state that, given what we observe in poor groups, such an origin cannot be ruled out, and is entirely plausible in some circumstances. In fact, given the current limitations of X-ray spectrographs, it is perhaps premature to have a debate on their Galactic vs. extragalactic origin. If we take lessons from other groups, such as NGC 1600, the z=0 systems most likely contain both Galactic and Local Group components, and also perhaps components from larger structures such as the Local Sheet. We predict that future higher resolution observations will resolve the z=0 systems in two or more components. One would be a low velocity component associated with the disk of the Galaxy and one or more may arise from extended structures. FUSE, which resolves low- and high-velocity components, has a spectral resolution of R=20000 in the medium resolution mode. Next generation X-ray spectrographs will have to have resolution of at least R=3000 (100 km/s) to begin to resolve different velocity components.

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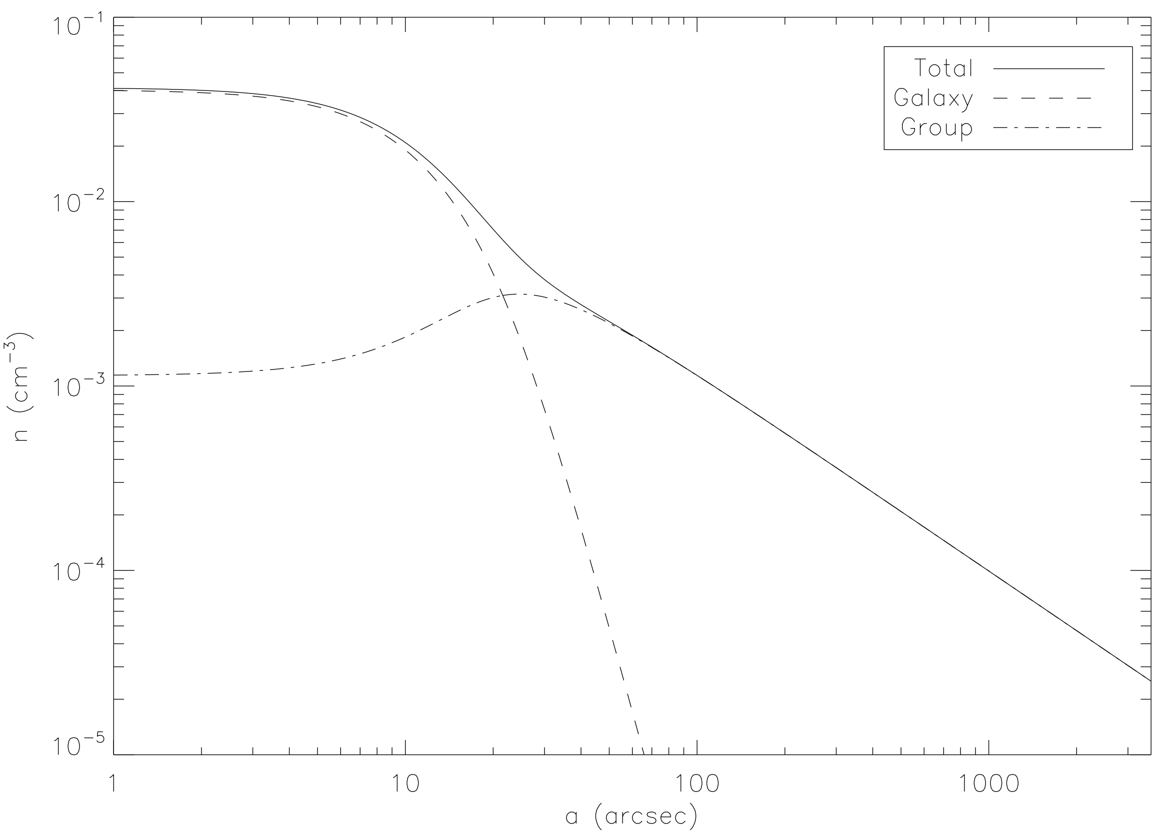

Fig. 1.— The gas density profile in the NGC 1600 galaxy (dashed line) and group (dot-dashed line). The solid line is for the total density profile.

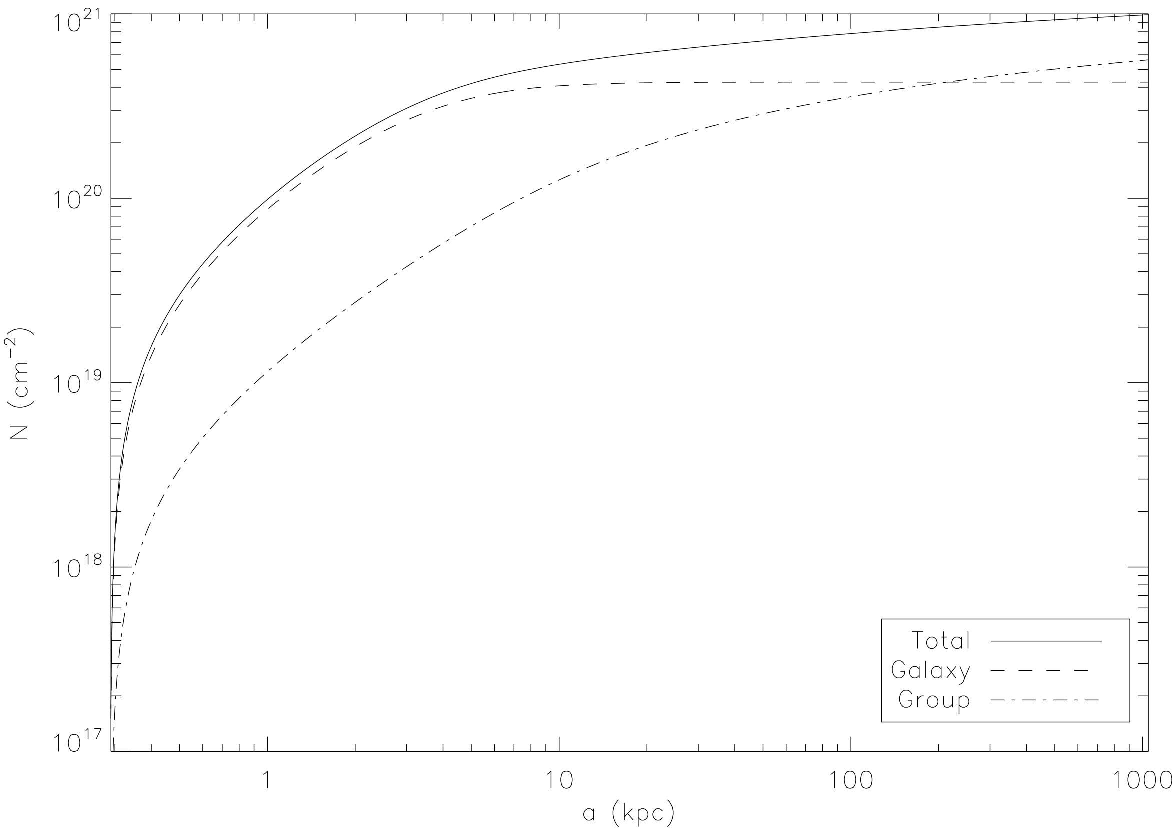

Fig. 2.— The column density through NGC 1600. The solid line shows the total column density while the dashed and dot-dashed lines mark the contributions of the galaxy and the group gas respectively. While the galaxy dominates the column density out to 200 kpc, the group column density dominates the total for longer sightlines.

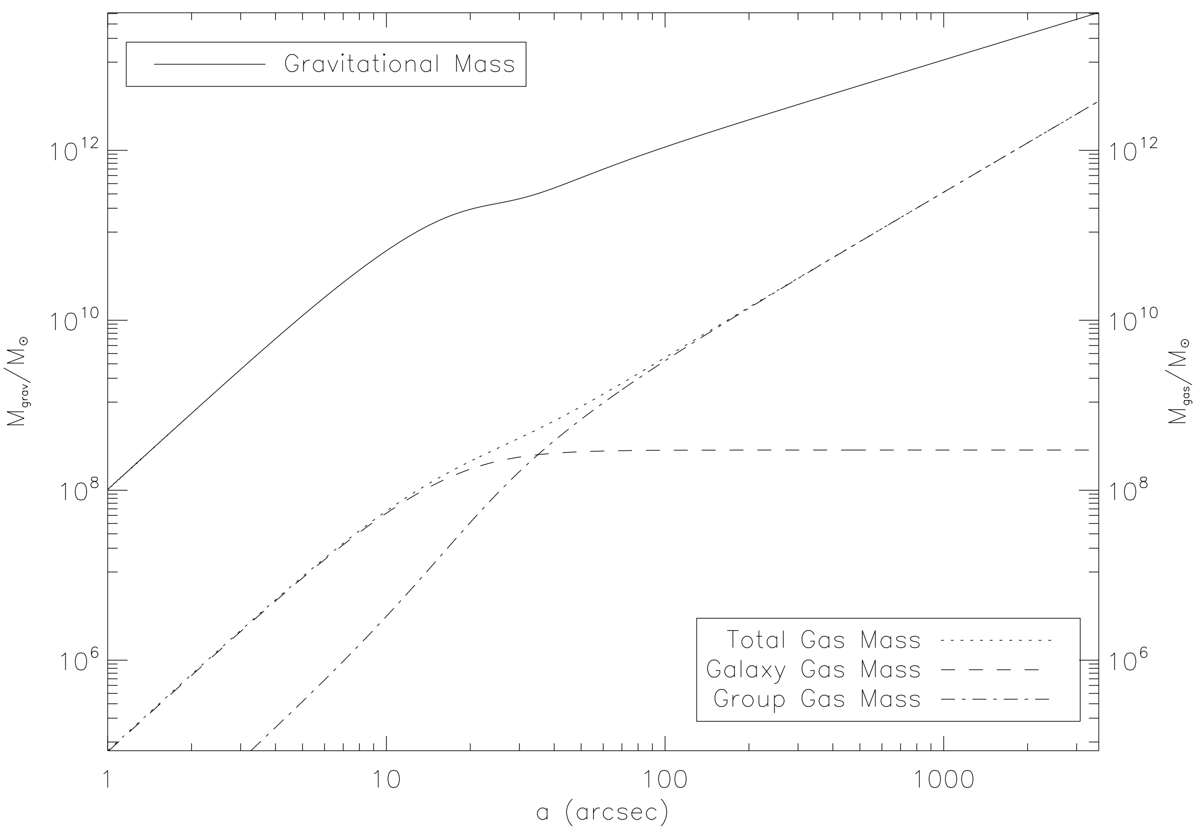

Fig. 3.— The gas mass profiles in the NGC 1600 group. The solid line is for the total gravitational mass (adapted from Paper I), which is significantly larger than the gas mass.